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CALIBRATION OF DYNAMIC PIEZOELECTRIC FORCE TRANSDUCERS USING THE HOPKINSON BAR TECHNIQUE

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ABSTRACT

Impact testing is an expanding research area in the industrial environment as well as in the academic field. Measurements during these dynamic events are mostly focused on acquiring the loads which occur. This makes dynamic force sensors the most important transducers during these impact experiments. Sensors using piezoelectric crystals are perfectly suited for recording dynamic loadings since the crystals exhibit an extremely high natural frequency and have an excellent linear behaviour over a wide amplitude range. However, these force sensors are difficult to calibrate, since they are unable to acquire static loads. Several calibration techniques already exist for calibrating these sensors. However, the most of them need other sensors which are also difficult to calibrate, and often expensive equipment is necessary. This work presents a new, fairly easy and inexpensive technique for calibrating dynamic piezoelectric force transducers, which does not need other sensors difficult to calibrate. It makes use of a split Hopkinson pressure bar setup in which the test specimen is replaced by a dynamic force sensor. It is shown that the striker bar with its launching system, which normally accompanies the setup and is the most expensive part of the test rig, is in principle not necessary for calibration purposes. This enables the construction of a low cost calibration device when compared to other existing calibration techniques. The force pulses generated in the setup can range up to 20 kN in magnitude and rise times of 50 μs at the shortest can be achieved.

Keywords: calibration, piezoelectric force transducers, dynamic force, Hopkinson bar technique

INTRODUCTION

For the last two decades, dynamic mechanical testing has become a growing field within the experimental research area. Especially the industrial demand towards impact testing has increased steadily. Intensive car crash tests, experiments on bird impact of turbine blades and water slamming tests on vessels may illustrate this. Reliable dynamic instrumentation is hereby essential in order to enable precise measurement of the desired data at high rate. Dynamic force transducers are one of the most important sensors used during these kinds of experiments.

To assure reliability of the force measurements, an appropriate calibration of these sensors is required. A few calibration methods exist, but they are not well established because of two reasons. First of all, this is due to the high technical expenditure necessary for most of the calibration setups. Secondly, most calibration devices need other sensors which are on their turn difficult to calibrate.

According to Fujii (Fujii, 2003), the existing methods can be divided into three categories: methods for calibrating dynamic force transducers against oscillation forces, methods for calibrating transducers against an impact force and methods for calibrating a transducer against a step force.

The calibration method using oscillating forces was first introduced by Kumme in 1998 (Kumme, 1998). He proposed a calibration method in which he connected a mass in series with the force sensor to calibrate. By shaking both the mass and the transducer with a harmonic excitation by means of a shaker, the inertial force of the mass was applied on the transducer. Calibration of the force sensor was then obtained by comparing the output of this sensor with the output of a reference force sensor, also connected to the system. Later on, Bruns et al (Bruns, 2001) adjusted this procedure by using calibrated accelerometers on the mass instead of a calibrated force sensor as reference instrument. Park et al (Park, 2002) used this method for dynamic investigation of multi-component force-moment sensors. However, this method is rather expensive, since there is a shaker needed to do the calibration experiments, as well as some extra force sensor or accelerometers. These reference sensors need to be calibrated as well, using other calibration techniques. Moreover, harmonic excitation is a rather unusual application in industrial dynamic force measurements and the calibration cannot be achieved for high force amplitudes and high force frequencies with this procedure, due to the limited power of the shaker (Bruns, 2001). Therefore, a new calibration procedure was required.

Fujii (Fujii, 1999) was the first in 1999 to propose another calibration procedure based on impact force. In this method, a force pulse was applied on the force sensor by making a mass collide with this transducer. After collision, the mass was immediately reflected creating a very short force pulse on the transducer. The position of the mass was hereby measured using an optical interferometer. This position was derived to velocity and acceleration and subsequently converted to impact force using the mass of the colliding object. Calibration could then be achieved by comparing this force value with the electrical output of the tested transducer. Fujii (Fujii, 2001 and Fujii, 2003) improved this method during the years, such as by measuring directly the acceleration of the mass by means of an accelerometer, instead of calculating the acceleration from the position. In the meantime, Bruns et al (Bruns, 2001) developed a similar procedure, which they called the Mass Impact Module. The difference with the latter method is that the force pulse was now generated by the central collinear impact of two masses with the transducer placed in between, instead of one mass. With this calibration method based on impact force, transducers could now be calibrated up to 20 kN and with pulse durations of 1 ms and less, which is closer to the impact events occurring in the industrial environment. However, expensive equipment is again necessary to measure the accelerations of the colliding masses (optical interferometer). Furthermore, difficult techniques are again required for calibrating this equipment. For the optical interferometer, calibration should result in finding a relationship between light intensities and distances.

The third category of calibration procedures as introduced by Fujii (Fujii, 2003) uses a known step force as reference. He introduced a method in which, at the beginning of the procedure, a heavy mass was suspended just above the transducer to calibrate with the use of a wire. Subsequently, the wire was cut and the mass was allowed to fall on to the transducer. The inertia force of the mass was thus again used as the calibration input. An optical interferometer was once more applied in order to evaluate the velocity of the mass during impact, which makes this method costly and difficult to calibrate again. This third calibration category also incorporates the calibration procedures which are provided by *PCB Piezotronics* (PCB Piezotronics, 2012), manufacturer of piezoelectric force transducers. This company determines the sensitivity of sensors with operating ranges from 22,24 to 444,8 kN by placing the force sensor in a hydraulic press stand and quickly applying or removing the force. A scaled down test stand is used for lower ranged sensors. In both cases, the applied force is measured by reference load cells. As in all previously mentioned methods, the same problems are encountered again: extremely costly equipment, and the need for calibrating the reference sensors.

In this paper, an innovative and low cost calibrating instrument for dynamic piezoelectric force transducers is presented. It makes use of two thin Aluminium circular bars and a few strain gauges which are used as reference sensors. Strain gauges can easily be calibrated by shunting them with a known resistance and reading out the voltage output of the Wheatstone bridge. Hence, no difficult calibration is needed for these reference sensors.

Force sensor calibration is performed by placing the sensor in between the two circular rods. An elastic stress wave, which is generated in the bars by hammer impact on one of the sides, is imposed on the force sensor and the strain gauges. Comparing the output of both sensor types enables the determination of the sensitivity factor of the tested sensor. This calibratrion procedure can be placed in the second category, as introduced by Fujii (Fujii, 2003). The test setup as described here is known as a split Hopkinson pressure bar setup (SHPB), which is usually employed as a device to investigate the mechanical properties of materials at high rate of loading (see Fig. 1). This setup has its name due to B. Hopkinson, who was the first to measure the shape of a stress wave in a long elastic bar (Hopkinson, 1914). Kolsky (Kolsky, 1949) was the first to use these fast-moving stress waves to test materials at high strain rate. A comprehensive review on the SHPB technique can be found in (Chen, 2011). Ueda and Umeda (Ueda, 1994) and (Färm, 2003) already showed that calibration of dynamic force sensors is possible with this technique. However, they used the complete setup as used for performing standard split Hopkinson experiments. We show that also a more simplified setup can be used, i.e. a Hopkinson setup without the common striker bar which is used to generate a plateau shaped stress wave in the bars. The apparatus used to launch this striker bar against the Hopkinson bar is the most expensive piece of the SPHB setup, thus by removing this part we succeed in finding a low cost calibration instrument for dynamic force sensors.

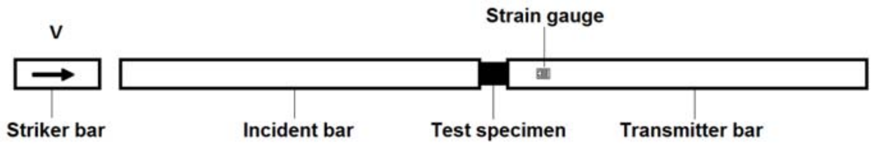


Fig. 1: Schematic overview of the split Hopkinson pressure bar setup

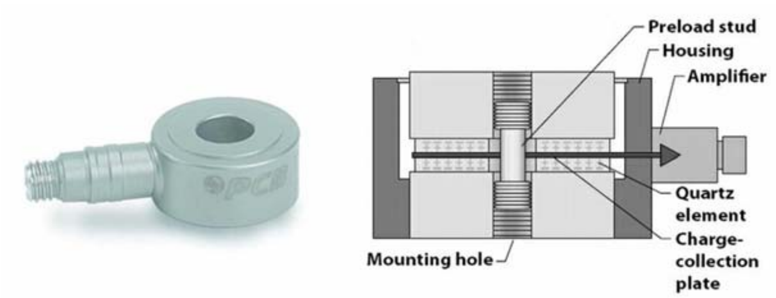
EXPERIMENTAL CONDITIONS

Piezoelectric Force Transducer

Force transducers for measuring dynamic forces are nearly always using piezoelectric crystals as their sensing elements. The principle is based on the fact that these types of crystals generate an electrostatic charge when being compressed which is proportional to the input pressure. This charge is subsequently converted into a low impedance voltage signal to enable readout with the appropriate instrumentation. Examples of common piezoelectric crystals are quartz, tourmaline (crystal materials) and lead zirconate titanate (PZT – a ceramic material). The reason why these crystals are well suited for recording dynamic loading events is the extremely high natural frequency they exhibit and the excellent linear behaviour over a wide amplitude range. The high frequency limit is mostly in the order 100 kHz and more, and is one of the most important characteristics of dynamic force sensors, commonly known as the resonance frequency (PCB Piezotronics, 2012).

In contrast with their excellent dynamic behaviour, piezoelectric crystals are unable to measure static loads. Even though the electrical insulation of the transducers is quite large, the electrostatic charge generated by compression will eventually leak to zero through the lowest resistance path. This makes that when a static load is applied to the sensor, the output will decrease to zero after some time, while the load is still present on the transducer. The rate at which the charge leaks back to zero is characterized by the discharge time constant (DTC) and is considered as the second important parameter of dynamic force gauges. This DTC is defined as the time required for a sensor to discharge its signal to 37% of the original value from a step input. The DTC is thus a measure for the low frequency limit of the transducer.

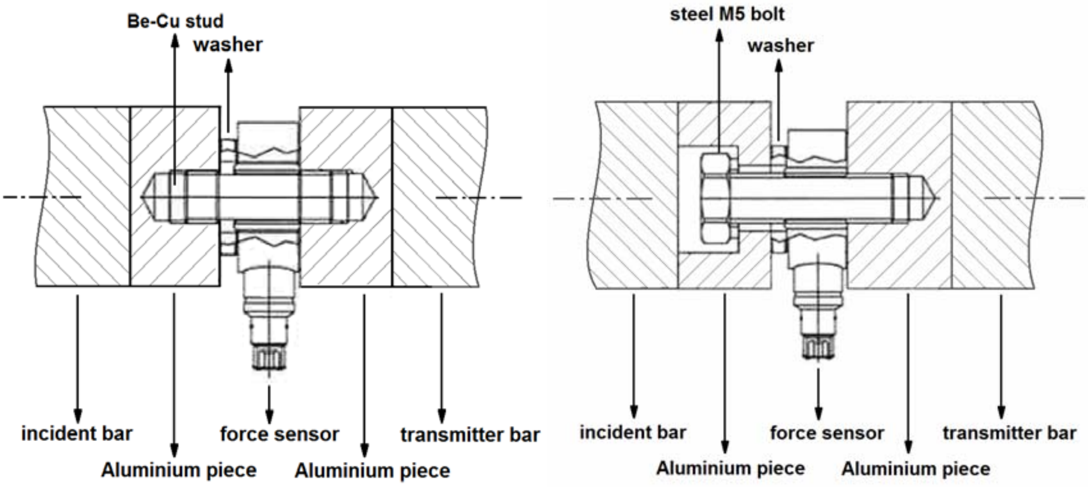
For the calibration experiments performed in this paper, a quartz crystal force sensor of type 201B05 from *PCB Piezotronics* is used. This transducer has a range up to 22 kN in compression and an upper frequency limit of 90 kHz. Fig. 2 shows the load cell and its internal components.



(a) (b)

Fig. 2: (a) Force sensor type 201B95 and (b) its internal components

To ensure output linearity also in the lower operating range, this sensor needs to be preloaded in the structure in which it is mounted using a preload stud, with a preload of 4500 N. Fig. 3 (a) and (b) show two configurations which can be used for this purpose as described in the sensor specifications of the used force transducer (PCB Piezotronics, 2012).



(a) (b)

Fig. 3: Photograph (a) and schematic intersection (b, c) of the force sensor connected between the Hopkinson bars using a Be-Cu stud (b) and a steel bolt (c)

In the typical installation, shown in Fig. 3 (a), the sensor is preloaded using an elastic Beryllium-Copper (Be-Cu) stud which is supplied by the manufacturer. The stud is provided with thread at both ends and is screwed in both parts of the construction. In this configuration, part of the force between the two structures is shunted trough the mounting stud. The amount of force shunted may be up to 5% of the total force for the Be-Cu stud according to the manufacturer. If another material is used for the stud, e.g. steel, this amount may increase up to 50 % (PCB Piezotronics, 2012).

The second installation type (see Fig. 3 (b)) uses a bolt to apply the preload on the force sensor. At the side of the bolt head, the bolt is not connected to the structure by providing a clearance between the structure and the bolt thread. At the other side, the bolt is screwed in the construction and preload is applied. In this configuration, the bolt does not shunt part of the force (PCB Piezotronics, 2012). This installation is used by PCB for calibration purposes and will also be used in this paper. A steel M5 bolt is used for mounting the sensor.

Split Hopkinson Pressure Bar Test Setup

A schematic overview and a photograph of the SHPB setup is depicted in Fig. 1 and Fig. 4.

Fig. 4: Photograph of the used split Hopkinson pressure bar test setup

The setup consists of a short striker bar, and a longer incident and transmitter bar. The incident and transmitter bar mostly have the same diameter. The test specimen is placed in between these two longer bars. In our setup, Aluminium bars are used. A test is performed by launching the striker bar with velocity V against the free end of the incident bar. The impact on this bar hereby generates a longitudinal stress and strain wave ε_i through the incident bar which propagates towards the test piece. The duration of this wave is determined by the length of the striker bar, while the magnitude is determined by the impact velocity V. A part of the wave is reflected back into the incident bar at the interface between the bar and the test specimen (ε_r). The other part is transmitted through the test specimen and propagates further in the transmitter bar (ε_t). Each bar is supported by bearings placed on V-shaped grooves in order to minimize the constraint on the elastic bars.

Under certain conditions, it is possible to calculate the time history of the strain ε, the strain rate $\dot{\varepsilon}$ and the stress σ in the test specimen from the measured time histories of ε_i, ε_r and ε_t. Three assumptions are therefore necessary (Peirs, 2007):

- The stress states in the Hopkinson bars and in the test piece are uniaxial.
- The test piece is at any time in a state of quasi-static equilibrium.
- The Hopkinson bars deform in the elastic region.

In reality, there might be some disturbing effects which make the calculations more complex, i.e. dispersion of the stress wave in the bars, and inertia and friction of the test piece. Since the force sensor (which is in this case the test specimen) has to be preloaded in the construction, it will be firmly fixed between the incident and transmitter bar, making the inertia and friction effects negligible. A photograph and schematic intersection of how the sensor is connected to the two bars is shown in Fig. 3 (b) and Fig. 5. The preload is hereby achieved by compressing the load cell between two Aluminium cylindrical pieces using the stud. These two Aluminium pieces are on their turn rigidly glued to the incident and transmitter bar.

Fig. 5: Photograph of the force sensor connected between the Hopkinson bars using a steel bolt

Dispersion effects arise from the wave propagation in the Hopkinson bars, but when the transversal dimensions of the bars are much smaller than the longitudinal dimensions, these effects may also be neglected. In the test rig used in this paper, the diameter of the bars is 25 mm which is much smaller than the lengths: 6 m for the incident bar and 3 m for the transmitter bar.

Neglecting the disturbing effects and considering the assumptions made above leads to a fairly easy calculation of the average stress history in the test specimen (Peirs, 2007):

$$\sigma_m(t) = \frac{A_s E_s}{2A_p}\left(\varepsilon_t(t) + \varepsilon_r(t) + \varepsilon_i(t)\right) \tag{1}$$

In this formulation, A_s and A_p are the cross-sectional areas of respectively the Hopkinson bars and the force sensor, and E_s is the Young's modulus for the material of the bars, i.e. the elasticity modulus for Aluminium (E_s = 71.5 GPa).

Since the two Hopkinson bars have the same material and the same intersectional areas, and as we assume that there is a quasi-static equilibrium in the test specimen because of its small length, following equation of equilibrium applies (Peirs, 2007):

$$\varepsilon(t) = \varepsilon_t = \varepsilon_i(t) + \varepsilon_r(t) \tag{2}$$

The average stress in test specimen then reduces to:

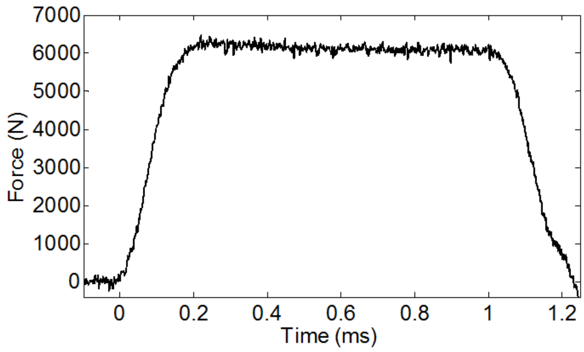
$$\sigma_m(t) = \frac{A_s E_s}{A_p} \varepsilon_t(t) \tag{3}$$

and the force acting on the force sensor becomes:

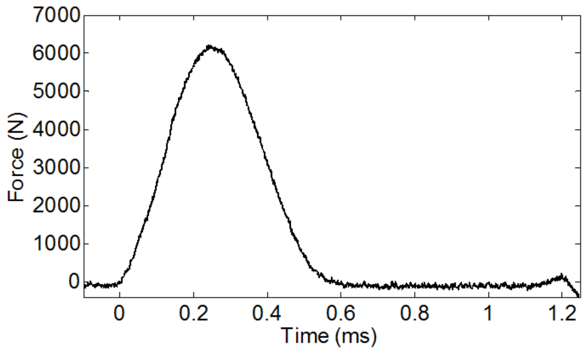
$$F(t) = A_s E_s \varepsilon_t(t) \tag{4}$$

This indicates that, when measuring the strain just behind the force sensor on the transmitter bar, the force acting on the force transducer can be measured. By comparing this force with the output of the force gauge, the sensitivity of the sensor can be determined. The strain on the transmitter bar is in this setup measured by two strain gauges in a half bridge configuration. They are of type FLA-2-11 Tokyo Sokki Kenkyujo, with a gauge factor of 2.11 and a resistance of 120 Ω. The distance between the gauges and the force transducer is 10 cm. Strain gauge calibration was performed before each experiment.

In this paper, however, the striker bar which is normally used in every standard Hopkinson test in order to achieve a plateau shaped stress wave is not used. The stress wave is here generated by a manual stroke of an industrial steel hammer. This will result in a pulsed shape wave. A comparison between both wave shapes is plotted in Fig. 6, as measured with the strain gauges.



(a)



(b)

Fig. 6: (a) Plateau shaped force wave generated by the striker bar; (b) Pulse shaped force wave generated by a common industrial steel hammer

The advantage of using a common hammer is that there is no pneumatical, mechanical or hydraulical launching system required for launching the striker bar against the incident Hopkinson bar. This reduces the costs of the test setup. Though, it does not reduce the ability of the test rig to act as a calibration device, since it does not matter for calibration purposes what shape the stress wave has. Only the difference in wave shape as measured by the force sensor and strain gauges is important in that viewpoint. This will be shown in the next paragraph.

EXPERIMENTAL RESULTS

Using the calibration procedure as presented in previous paragraph, 41 calibration experiments were performed with the force sensor of type 201B05 preloaded with a steel stud using the installation configuration of Fig. 3 (c). Fig. 7 shows the ratio of the maximum of the force pulse, as measured by the strain gauges and by using equation (4), to the maximum of the voltage output of the force transducer for each experiment. This ratio represents the calibrated sensitivity of the force sensor preloaded with a steel stud, and has an average value of 4.93 *N/mV*. The uncertainty of the calibration experiments is estimated as 1.28%, using the variation coefficient, which is fairly small, indicating a good reproducibility of the measurements

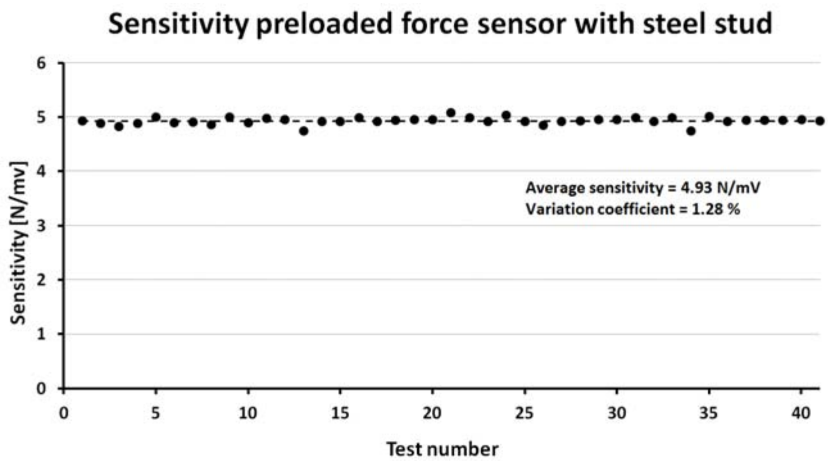
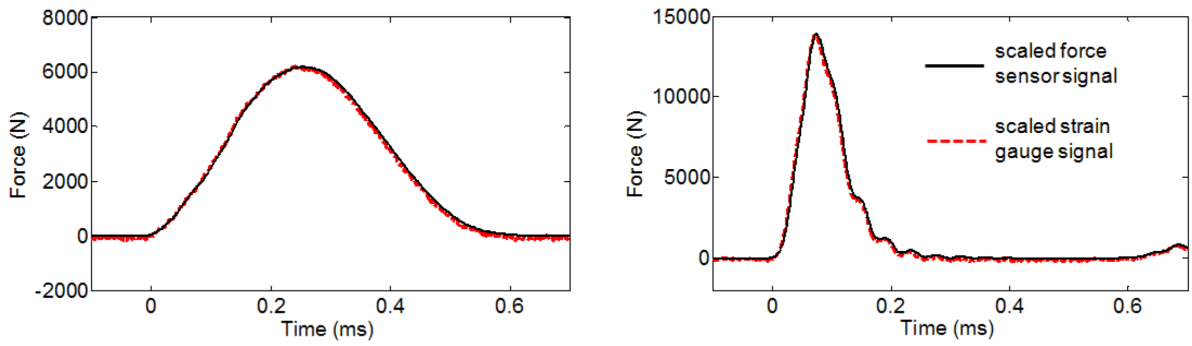


Fig. 7: Sensitivity coefficient for 41calibration experiments for sensor of type 201B05 preloaded with a steel stud

(a) **The previous graph only considers the peak values of the force pulses which travel through the Hopkinson bars. Also the force-time traces of the signals measured by the force transducer and the strain gauges should be compared.** (b)

Fig. **8** shows the time history of the force, as measured by the strain gauges and using equation (4) (in red), compared to the force trace measured by the force sensor and using the determined sensitivity factor of 4.93 *N/mV* (in black). This comparison is made for a middle force amplitude and a high force amplitude. In both cases, a perfect match can be noticed concerning the shape and magnitude of the pulses. This shows that the presented method can be successfully used as a calibration procedure for dynamic force transducers.



(b) (b)

Fig. 8: Comparison of the force-time traces of the load pulses as measured by the force sensor (black) and the strain gauges (red): (a) is for a middle force amplitude, (b) is for a high force amplitude.

The determined sensitivity ratio can also be applied as illustration on a plateau shaped stress wave, by using the striker bar of the Hopkinson setup. Fig. 9 shows again that the time histories of the force as measured by the force transducer and the strain gauges are corresponding exactly using the determined sensitivity factor. This correspondence in the sensitivity of the force sensor determined by the hammer pulses and the one applicable when generating pulses using the striker bar shows that using a common industrial hammer instead of the striker bar of the Hopkinson setup does not reduce the quality of the calibration.

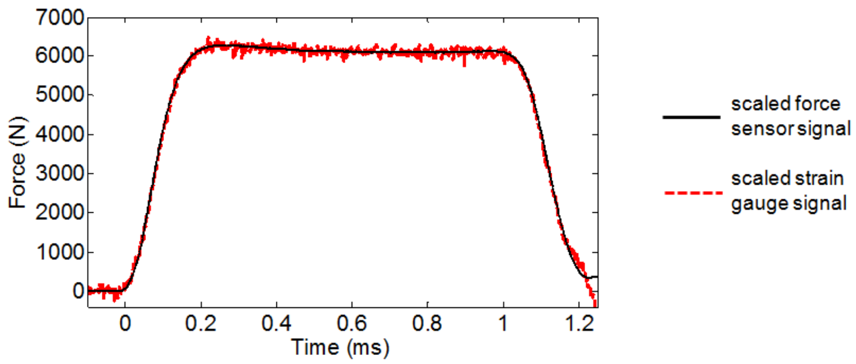


Fig. 9: Comparison of the force-time trace of a plateau shaped load pulse generated by the striker wave as measured by the force sensor (black) and the strain gauges (red).

The maximum range of forces which can be applied on the force transducer depends on how hard a person can hit the incident bar with a hammer. In the test series for this paper, forces up to 14 kN were tested. Fig. **10** gives an overview of the forces which were generated during the calibration experiments. This maximum limit might reach 20 kN, since the hammer has not been used with full power in this test series, in order to avoid overload of the force gauge. If transducers with higher range need to be calibrated, it can be considered to use the fully equipped split Hopkinson pressure bar setup, including the striker bar, which can go up to forces of 40 kN (Peirs, 2007). However, then the costs will increase.

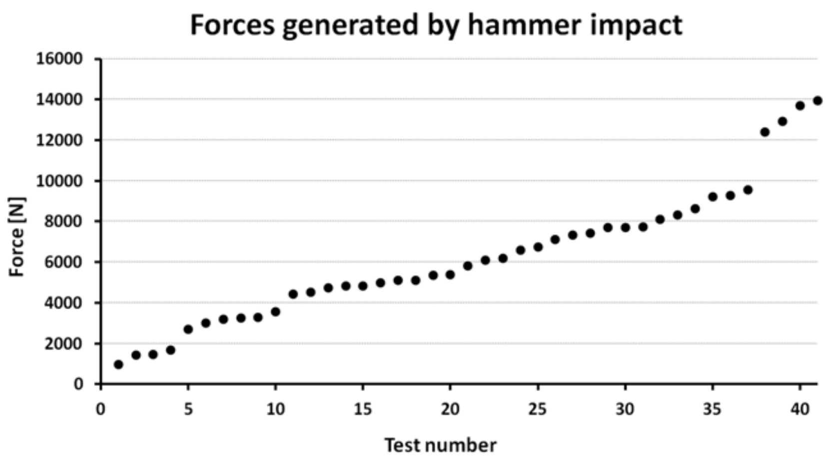


Fig. 10: Overview of the force amplitudes of the load pulses which were generated in the Hopkinson bars using a steel hammer

From Fig. **8** (b), it can also be observed that very short rise times of the force pulses can be achieved by the present setup. The rise time is the time between the start of a force pulse and the time when its maximum value has been reached. Fig. 11 shows the rise time of the generated force pulses in climbing order. The shortest rise time is in the order of 50 µs which shows that this calibration setup is suited to generate highly dynamic force pulses, which regularly occur in the industrial environment.

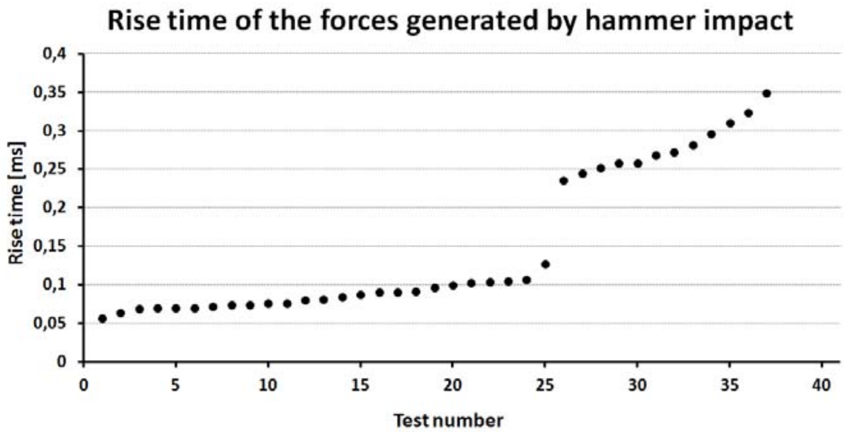


Fig. 11: Overview of the rise times of the load pulses which were generated in the Hopkinson bars using a steel hammer

CONCLUSION

The experiments performed in this paper show that the split Hopkinson pressure bar setup can be successfully used as a calibration device for dynamic piezoelectric force transducers. It is shown that proper calibration can be achieved by using a common industrial hammer for generation of the force pulses, instead of the striker bar and its accompanying launching system, which is normally used in each Hopkinson setup to obtain plateau-shaped force pulses. The presented calibration device can thus be considered as an inexpensive alternative for other existing calibration techniques for dynamic force sensors.

Experiments were performed with the preloading configuration using a steel bolt as described in the user guidelines provided by the manufacturer of the used force transducer. Consistent results for the sensor sensitivity were obtained with an uncertainty level of 1.28 %. The setup is suited for calibrating force sensors with a range up to 20 kN and is able to generate force pulses with a rise time of 50 μs at the shortest, indicating that the setup is able to generate highly dynamic force pulses which are very close to realistic events.

To improve the control over the force magnitude and the rise time of the force pulses, it can be considered to suspend the striker hammer as a pendulum, and vary the drop angle, as is depicted in Fig. 12. Moreover, this pendulum could be actuated by an adjustable torsional spring or an actuator to get even higher or shorter force pulses.

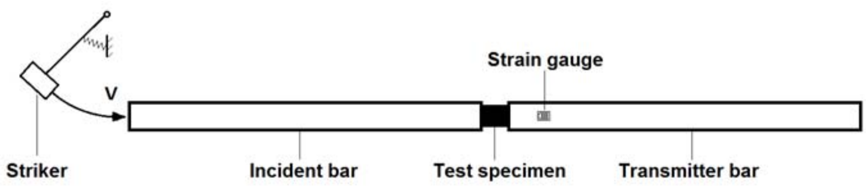


Fig. 12: The split Hopkinson pressure bar setup using a striker hammer suspended as a pendulum and using a torsional spring

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